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CONSCIOUSNESS BEGAN WITH A HUNTER'S PLAN

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ABSTRACT: Animals search for food and shelter by locomotion through time and space. The elemental step is the action-perception cycle, which has three steps. In the first step a volley of action potentials initiated by an act of search (sniff, saccade, etc.) triggers the formation of a macroscopic wave packet that constitutes the memory of the stimulus. The wave packet is filtered and sent to the entorhinal cortex, where it is combined with wave packets from all sensory systems. This triggers the second step forming a unified memory that is passed through the hippocampal formation where it is assigned a place in the life-long memory of the subject. In the third step the output of the entorhinal cortex triggers the formation of a global wave packet that synchronizes the oscillatory activity of most of not all of the cerebral cortex. This shared oscillation caries a pattern of amplitude modulation, that can be observed non-invasively from the scalp EEG of human volunteers perceiving the stimulus and correlated with the stimulus. The same dendritic electric currents that drive the output of the brains of the wave packet drive the observed EEG signs. Therefore I postulate that the global wave packet, the third step in the cycle requiring only 0.2 seconds expresses the memory of the global accommodation that initiates the next action-perception cycle. Some unspecified fraction of the AM pattern is available to me the observer, and some other unspecified fraction of the total activity in the subject who is expected to respond to the stimulus. There is reason to hope that these fractions will coincide often enough to support refinements in techniques for extending these correlates of consciousness.

KEYWORDS: Action-perception cycle; consciousness; EEG; entorhinal cortex; phase transition

WHERE IS CONSCIOUSNESS FOUND?

My first premise is that only firm evidence for the existence of consciousness in any being other than one's self cones by inference from observing goal-directed behaviors and participating in cooperative or destructive relationships: hunt and be hunted. All else is speculation.

My second premise is that primitive conscious beings emerged in the Cambrian Sea half a billion years ago in multiple forms. They engaged in Darwinian competition of eat or be eaten and thereby evolved increasing complexity. William James postulated that the advance took the form of "… an organ added for the sake of steering a nervous system grown too complex to regulate itself." [James 1879, p. 18]. Thee necessary though not sufficient condition for emergence was growth in the sizes of the brains and bodies that are exemplified by the sizes of organisms with which today we car engage on terms of accessibility. Some 200 million years later the first vertebrates emerged with a significant concentration of neurons in the primordial forebrain (Figure 1) consisting of the two hemispheres enclosed in a helmet-like skull. The anterior third of each hemisphere was sensory (predominantly olfactory), the lateral third was motor (mainly for the jaws), and the medial third was for navigation (the primitive hippocampal formation).

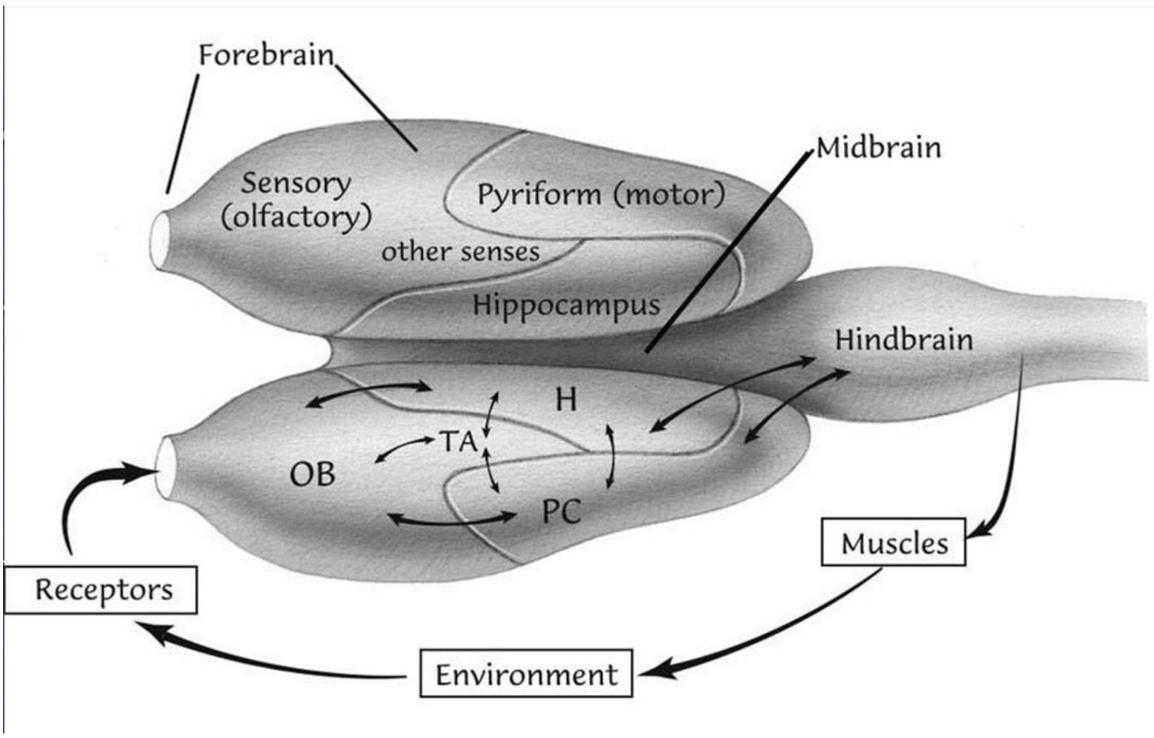

Figure 1

At the center of each hemisphere was a small transitional area labeled "TA" by Herrick [1948], which received input from other sensory systems (vision, audition and body). As brains evolved, this area greatly expanded while preserving the close functional connections with each other in a ring along the edge of each hemisphere, which has been retained as the limbic system. The organization of the brain makes sense only when it is seen as having been shaped by the requirements for phylogenetic and embryological unfolding. From this perspective the topological center of the forebrain is not the thalamus but the entorhinal cortex, which was the first six-layered neocortex to emerge at "TA" from the three-layered primitive allocortex. Neocortex with its potential for avast surface area expanded the arms race and the importance of consciousness as the weapon of choice.

My third premise is that the "organ" added by evolution was neuropil, which is a sheet of neurons and neuroglia that are densely packed and interconnected by innumerable channels conducting chemical and electrical fields of energy, and by specific mechanisms of engagement of neurons in dyadic pairs through synapses. The tissue contains the cell bodies of the neurons and neuroglia and a capacious capillary network that brings oxygen and nutrients and removes carbon dioxide, heat, and other waste products from the extremely high rates of metabolism. The neurons typically form layers and palisades with dendrites aligned perpendicularly to the sheets called laminated neuropil, which is better known in vertebrate brains as cerebral cortex.

Neuropil is found in all vertebrates and in the more behaviorally sophisticated invertebrates, such as cuttlefish among mollusks and bees among arthropods. Interactions are en masse, owing to the extreme packing density of the cells and their dendrites and axons. The dynamics must be described by use of continuous variables in space, time and energy in differential equations or equivalent [Freeman 1975]. Neuropil embeds neural networks with discrete synaptic dyads. Two levels of function are required. At the microscopic level the dynamics of neurons and synapses is observed by recording action potentials of small representative sample of cell bodies and axons. At the macroscopic level the dynamics or neural populations is observed by recording EEG waves generated by hundreds of millions of neurons. I postulate that the dense activity of neuropil expressed in continuous macroscopic images is required by brains in order to construct and express the memories that humans experience in their customary richness of detail. My goal in this report is to make the case that consciousness grew from the need for food, sex and shelter, that neuropil provides the mechanism, and that the neural operations are observed subjectively in awareness and objectively in wave patterns from EEG signals.

A CANDIDATE FOR A RELIABLE NEURAL CORRELATE OF CONSCIOUSNESS

From these premises it follows that Consciousness is a biological process that is sustained by coordination of activity in many parts of the brain of a subject who is engaged in an action of searching for information that it needs to cope with its environment. The element of search is the action-perception cycle or "intentional arc" of Merleau-Ponty (1949/1962). The neuron populations sustaining the process generate electrical signs of activity while doing the work of directing the search. These signs are the action potentials of axons and the field potentials of dendrites, which are recorded as EEGs and LFPs from sensory, motor and limbic cortices during a single sniff comprising an action-perception cycle, specifically in one of the sniffs in the time segment between the onset of a conditioned signal (CS) and the onset of the following conditioned response (CR) in behavioral testing.

I choose the olfactory sensory system as my example, because it was the first to evolve, and thereby offered an archetype for development of adaptations of cortical dynamics in all sensory ports. Each inhalation is correlated with a wave packet, that is, a burst of 3-5 cycles of gamma activity in the EEG [Freeman, 2001], which was the sign of synchronization of the entire olfactory system and all its parts. Thereby it gave the opportunity to test the hypothesis that the bulb coded odorants spatially, by recording the EEG simultaneously from 64 electrodes in an 8x8 array serving as a window to detect spatial amplitude modulation (AM) of the gamma wave. Indeed the results proved that gamma waves and beta waves as well over a broad range of frequencies carried AM patters that could be classified and categorized with odorants, but only if the subjects learned to respond to them as CSs through reinforcement training in classical or instrumental paradigms. It turned out that the AM pattern was not a representation of the stimulus; it was the sign of the memory of the CS, which changed with experience from each trial set to the next.

This insight led the way to investigation of AM pattern formation in the EEGs of the somatic, auditory and visual cortices [Barrie et al., 1996], which confirmed the hypothesis that all these systems worked the same way. A volley of action potentials from excitation of sensory receptors by CS in an action-perception cycle triggered the formation of an AM pattern of a gamma wave packet that carried the memory of the CS. The memories were updated by the input volley and stored locally while being transmitted broadly and most importantly to the entorhinal cortex. There the memories are combined into a multimodal memory, by virtue of the fact that they all have the same form of feature vectors that can be integrated by vectorial concatenation, thus ensuring the unity of perception from an action-perception cycle.

The construction of the meaning of the multimodal memory requires multiple samples in sequence. The subject must remember the strength of odor long enough to compare it with the next sample. It must also remember where it was and when it sampled, and what action in chose at the previous sample, and it must have confirmation by proprioception from the somatosensory system that the intended action was actually taken, in order to determine what to do in the next cycle. All this is the work of the hippocampus. Space-time labeling is required for every sensory modality, which explains why the primitive architecture of the primordial vertebrate brain has been retained in the limbic system of mammals. It also explains why perception is necessarily cinematic. Each new percept has no meaning until it is embedded in the life history of the subject, and that takes time and memory.

The hippocampus completes the action-perception cycle by returning the labeled percept to the entorhinal cortex. The onset of the next action-perception cycle is contingent on the brain making optimal use of the updated percept to prepare for the next act of exploration following that just completed. The preparation includes updating the directional stance of strategic action planning, the tactical adjustments of motor components, the pre-afferent priming of focused sensitivity in every primary sensory cortex in the accord with the latest information from the same and every other primary sensory cortex, and recruitment of the entirety of experience stored in the neuropil. All this must be done in little more than a tenth of a second.

THE HIDDEN SECRET OF CONSCIOUSNESS

My hypothesis holds that a known stimulus triggers a sequence of three phase transitions [Ruiz et al., 2010]. In the first transition the cortex receiving the CS shifts abruptly from a gas-like phase to a liquid-like phase at a high level of energy density and transmits the local memory of the CS to the entorhinal cortex. The second phase transition is in the entorhinal cortex, which is triggered by the integration of the signals from all of the sensory systems. The third phase transition is triggered by the entorhinal cortex under the influence of the hippocampus and related parts of the medial temporal lobe

All three of these transitions manifest a change in the neuropil from a gas-like, low-density, incoherent noise-like activity to a narrow-band, energy-intensive, synchronized oscillation. In each step the synchronized wave has the capacity to carry a high-dimensional pattern, to which all synchronized neurons might contribute their increments of memory. The range in size of AM patterns from local to global indicates that the transitions are independent of size, hence scale-free, and can include the entire neuropil of the cerebral cortex. This astonishing fact, that a global interactive field can form in a few msec, persist for a tenth of a second, dissolve, and form again, calls for a bold hypothesis. The global phase transition suggests the simultaneous adaptation and assimilation by each sensory and motor cortex of its content with every other cortex through the channels created by the synchronizing field. The neural mechanism of interaction by fields, as postulated by Wolfgang Köhler (1940), Karl

Pribram (2013) and others, can in principle explain how the brain can choose a coordinated an action for the body to take, and prime all sensory cortices on what new sensory input to expect, and do this in the time duration from one sniff to the next This suggests that the duration of a wave packet can serve as a measure of William James' "now" in psychological time.

The experimental evidence for this global cooperation has come from a standard clinical 64-channel recording of scalp EEG from six volunteers. [Ruiz et al., 2010]. The subjects were asked to attend to sequences of somatic and visual stimuli in randomized order, and to press a button whenever a specified combination occurred. Beta and gamma bursts were located in the CS-CR interval, and the AM pattern of each burst was measured and expressed as a point in measurement space. The AM patterns in scalp EEG gave a tight cluster of points at minimally three successive time segments in the CS-CR interval, which were significantly classified as correlated with the presentation of the specified CS. The important finding was that the classifying information in the EEG was not localized, Systematic search by removing randomly chosen signals from the 64 electrodes showed that each electrode gave a signal that had no more or less value than any other signal for classification. Why was this important? It proved that the memory signaled by the EEG was spatially distributed over the extent of the synchrony of the carrier wave. It was crucial because each cortex sent its readout to many targets, and every target got the same full readout as every other. My logic is that since the EEG presents information to me about the stimulus, that information is also contained in the firing patterns of neurons in the neuropil, whose firing is controlled by the dendritic currents that contribute to the EEG.

This simple non-invasive experiment has been reproduced by recording from the scalp with different space and time scales, and with different methods of locating the beta-gamma bursts [Freeman and Quian Quiroga, 2013]. Obviously multiple bursts overlap with differing AM patterns in the multichannel EEG recordings, with varying start and end times. The brevity of the wave packets makes them difficult to capture by trolling through the data with digital filters. The design of optimal adaptive filters is the first of the Grand Challenges faced by neuroscientists seeking to explain consciousness.

The second Grand Challenge is to explain how each global AM pattern condenses over the entire cortex within the time span of a quarter cycle of the carrier frequency, for example 5 msec for a 50 Hz burst, how it sustains its action for 3 to 5 cycles (60-100 msec), and how it is evaporates quickly to organize the next wave packet that implements the action-perception cycle. These events exceed the capacity of conventional neurophysiology for explanation. Clearly the cerebral cortex maintains itself in a critical phase of chaotic disorder, from which it can transit to an ordered phase with controlled dissipation of energy for patterned firing needed to cope with environmental contingencies. An salient possibility is that the phase transition can be modeled using the formalism for the Bose-Einstein condensate [Freeman and Vitiello, 2008; Marshall, 1989] as s a heuristic metaphor to help explore these macroscopic phenomena, perhaps to explore the role of water dipoles in massive synchronization of firing in the neuropil by ephapsis [Anastassio et al., 2011].

Another approach will be to use fMRI and other imaging techniques to measure the energy used for the construction of knowledge from information that has been collected by the action-perception cycle can be indexed by measurement of the beta-gamma bursts. It is well known that brain function is extremely energy-intensive. Cortex dissipates metabolic energy at rates ten times greater per unit mas than other organs in the body. By using the Carnot cycle to define our state variables, we can begin to explore more deeply the metabolic cost of consciousness [Capolupo et al., 2013].

The third Grand Challenge is David Chalmer"s [1996] "hard problem" of finding a causal relation for consciousness, whether it is proactive, enactive, judgmental, or epiphenomenal. The problem is best left to philosophers.

CONCLUSION

In the Darwinian competition for survival and procreation the greatest asset is a clear understanding of a problem to be solved is a concise organization of information about the situation of the body in an environment requiring action. The mechanism is provided by the action-perception cycle, which emerged over the past half billion years as the meams for mobilizing energy in brains to bring to bear on an impending crisis the most relevant portions of a subject's experiential resources. My hypothesis is that the summary action is expressed in a global field of synchronized oscillation, which will shape the next action. My conjecture is that we experience this wave packet as consciousness. How and why it comes in the form that it does are "hard problems" for debate. From the biological standpoint we have work to do. We have only recently acquired the tools and the brain theory that are essential for successful exploration. We need not reify consciousness into a force of nature or a property of matter. Rather wee need to improve our filters so as more effectively to decompose our EEG data and measure more precisely the wave packets and the phase transitions, when the cortex briefly switches from exponential time to polynomial time, in order to concentrate metabolic energy into dynamical structure. Brain science now ever more clearly poses problems in basic physics, for which the solutions may require major modification of the methods of modeling that have been devised for modeling other collectives of matter. In particular, neuropil is a unique form of matter that will require physicists to devise unique models. We need to overcome the limitations and treat EEG, ECoG and LFP as extremely complex signals, not noise, and realize their true value as ever-renewing sources of information revealing how brains make up their minds.

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REFERENCES

Anastassiou CA, Perin R, Markram H, Koch C [2011] Ephaptic coupling of cortical neurons. *Nat Neurosci* 14:217–223.

Barrie JM, Freeman WJ, Lenhart M [1996] Modulation by discriminative training of spatial patterns of gamma EEG amplitude and phase in neocortex of rabbits. *Journal of Neurophysiology* 76: 520-539.

Buzsaki G (2003) *Rhythms of the Brain*. Oxford UK: Oxford UP.

Capolupo A, Freeman WJ, Vitiello G (2013) Dissipation of 'dark energy' by cortex in knowledge retrieval. *Phys.Life Reviews*, on-line. DOI: 10.1016/j.plrev.2013.01.001

Chalmers DJ (1996) *The Conscious Mind: In Search of a Fundamental Theory*. Oxford UK: Oxford UP.

Freeman WJ (2001) *How Brains Make Up Their Minds*. New York: Columbia UP

Freeman WJ (1975) *Mass Action in the Nervous System*. New York: Academic.

Freeman WJ (2011) Understanding Perception Through Neural 'Codes'. In: Special Issue on "Grand Challenges in Neuroengineering", *IEEE Trans Biomed Engin* 58 (7): 1884-1890. DOI: TBME-00851-2010.R1

Freeman WJ and Quian Quiroga R (2013) *Imaging Brain Function with EEG*. New York: Springer.

Freeman WJ, Vitiello G [2008] Dissipation and spontaneous symmetry breaking in brain dynamics. *J Physics A: Math, Theory* 41 – 304042 (17 pp) doi:10.1088/1751-

8113/41/30/304042. http://stacks.iop.org/1751-8121/41/304042 http://repositories.cdlib.org/postprints/3385.

Herrick CJ (1948) *The Brain of the Tiger Salamander*. Chicago IL: University of Chicago Press.

James W (1879) "Are we automata?" *Mind* 4: 1-21.

Kay LM [2003] Two species of gamma oscillations in the olfactory bulb: dependence on behavioral state and synaptic interactions. *J Integrative Neurosci* 2(1): 31-44/

Köhler W (1940) *Dynamics in Psychology*. New York: Grove Press.

Marshall IN [1989] Consciousness and Bose-Einstein condensates. *New eas Psycho*. 7(1): 73-83.

Merleau-Ponty M (1945/1962) *Phenomenology of Perception*. (C Smith, trans.). New York: Humanities Press.

Pockett S, Bold GEJ, Freeman WJ [2009] EEG synchrony during a perceptual-cognitive task: Widespread phase synchrony at all frequencies. *Clin Neurophysiol* 120: 695-708. doi:10.1016/j.clinph.2008.12.044.

Pribram KH (2013) *The Form Within. My Point of View*. Westpoort CT: Prospecta Press.

Ruiz Y, Pockett S, Freeman WJ, Gonzales E, Li Guang (2010) A method to study global spatial patterns related to sensory perception in scalp EEG. *J Neuroscience Methods* 191: 110-118. doi:10.1016/j.jneumeth.2010.05.021.